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Final Report

A Consortium For Ocean Circulation And Climate Estimation

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OVERALL GOALS and OBJECTIVES

Our goal was to bring ocean state estimation from its early experimental status to a practical and quasi-operational tool for studying large-scale ocean dynamics, for designing observational strategies and for examining the ocean's role in climate variability. Our central technical goal was a complete global-scale ocean state estimation over at least the 15 year period 1985-2000 at 1/4° resolution with a complete error description and regional refinements to support CLIVAR and GODAE needs. For that purpose we intended to combine all available large-scale data sets — including TOPEX/POSEIDON, TOGA-TAO, high-resolution VOS XBT/XCTD, profiling floats, and drifters — with the dynamics embodied in a general circulation model to estimate the time-evolving, three-dimensional physical state of the full oceanic circulation.

Our central focus was on the state estimation of the global ocean in its entirety combining together into a coherent whole all suitable data sets. Our interest was to draw models and observations together over decades of time to arrive at a complete (i.e., including aspects not directly measured) dynamical description of ocean circulation, such as insights into the natures of climate-related ocean variability, major ocean transport pathways, heat and freshwater flux divergences (similar for tracer and oxygen, silica, nitrate), location and rate of ventilation, and of the ocean's response to atmospheric variability.

The ECCO activities were performed in three groups located at MIT (J. Marshall, and C. Wunsch), JPL (I. Fukumori, L.-L. Fu, T. Lee, D. Menemenlis, and V. Zlotnicki) and SIO (D. Stammer (PI), R. Davis, P. Niiler). Each institution had its own task within the entire approach as described below, covering model development, estimation activities, data preparation and scientific analyses. This report is the final report for only the SIO component of the ECCO work.

All ECCO results obtained from the SIO group are available to the wide community via internet through the projects Life-Access-Server (LAS) at http://www.ecco-group.org/las. At the ECCO web page http://www.ecco-group.org a full account of ECCO Project reports and publications is provided.

ACCOMPLISHMENTS

At SIO, activities by D. Stammer and his group were centered around performing the global ocean state estimate using the adjoint model and improving its results. Our focus was on the state estimation of the global ocean in its entirety combining together into a coherent whole all suitable data sets. Our interest was to draw models and observations together over decades of time to arrive at a complete (i.e., including aspects not directly measured) dynamical description of ocean circulation, such as insights into the natures of climate-related ocean variability, major ocean transport pathways, heat and freshwater flux divergences (similar for tracer and oxygen, silica, nitrate), location and rate of ventilation, and of the ocean's response to atmospheric variability.

This work was subdivided into several efforts that will be described separately below.

1. 2° Global Optimization

The first outstanding result of the ECCO work was that we were able to complete a first global ocean state estimation of the time-varying circulation over the 6-year time interval 1992 through 1997 on a 2° spatial model grid. Data employed in in that first optimization included the absolute and time-varying T/P data from October 1992 through December 1997, SSH anomalies from the ERS-1 and ERS-2 satellites, monthly mean sea-surface temperature data (*Reynolds and Smith*, 1994), time-varying NCEP reanalysis fluxes of momentum, heat, freshwater, and NSCAT estimates of wind stress errors. Monthly means of the model state were required to remain within assigned bounds of the monthly mean *Levitus et al.* (1994) climatology. To bring the model into consistency with the observations, the initial potential temperature (θ) and salinity (S) fields were modified, as well as the surface forcing fields. Changes in those fields (often referred to as "control" terms) were determined as a best-fit (in a least-squares sense) of the model state to the observations and their uncertainties over the full data period.

D. Stammer performed a considerable analysis of the model output with respect to its realism, and with respect to time-varying ocean circulation and transports. Together with the MIT group, D. Stammer prepared altimetric data and other WOCE data input of the optimization. Equally important many large-scale data sets were processed for a comparison of the existing ocean state with independent data. In the next experiments (see below) these fields were then included in the optimization which include the global WOCE hydrography, the global XBT data set (including the TAO data) and the preparation of the global surface drifter data set (P. Niiler) and float fields (R. Davis).

A few early ECCO results are summarized in Figs. 1. Among them, the estimated mean velocity field at 27 m depth (top panel) shows all major current systems. But with the low model resolution, they are necessarily overly smooth. Shown in the lower panel of the figure is a bottom pressure record from the constrained and unconstrained models which compare in detail strikingly well to observed bottom pressure records. The figure illustrates how close even the unconstrained model is in simulating the observed bottom pressure variability, especially in its high-frequency part. The estimation is indeed capable of improving the agreement, especially on the annual cycle.

We use this early model-based synthesis for a first dynamical description of the time-evolving ocean circulation, its major ocean transport pathways, heat and freshwater flux divergences and of the ocean's response to atmospheric variability. Respective results were published in several papers, including Stammer et al. (2002, 2003).

2. 1° Global Optimization

We continued the earl work by extending the estimation period from 6 to 10 and later to 12 years

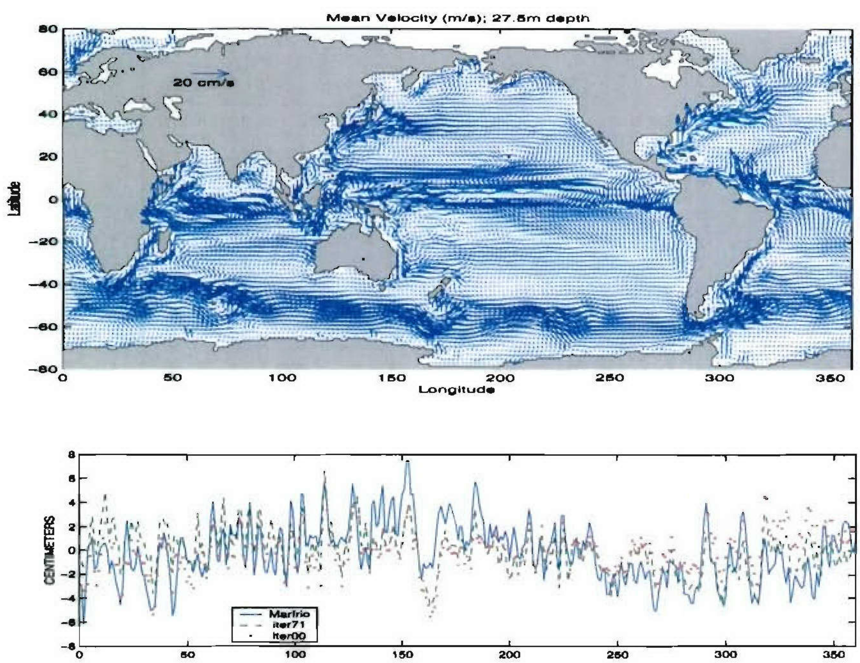

Figure 1: ***(top)The estimated mean velocity field at 27.5m as it results from the 6 year assimilation period. (bottom) Timeseries of the bottom pressure of the constrained (green dashed lines) and unconstrained (red dots) models with bottom pressure measurements from the "Marfrio" location at 32°S, 36°W in the South Atlantic.***

(1992 through 2002), by increasing the horizontal resolution, and by extending significantly the data sets used to constrain the model. The result of that second optimization was that we were able to obtain a complete global ocean data synthesis that provides an estimate of the time-varying circulation over the 10-year time interval 1992 through 2002, that is nearly consistent with most available global data sets. Data employed include the entire suit of in situ data, altimetry, SST and scatterometry; in particular we use already all available ARGO and PALACE temperature and salinity profiles as constraints. Moreover, we use time-varying NCEP reanalysis fluxes of momentum, heat, freshwater, and NSCAT estimates of wind stress errors. Monthly means of the model state are required to remain within assigned bounds of the monthly mean *Levitus et al.* (1994) climatology and a drift of the model over the 10 year period is penalized to bring the model hydrography into a stable equilibrium with surface fluxes.

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The most outstanding result of the ECCO global synthesis on a 1 degree grid was that we were able to obtain a complete global ocean data synthesis that provides an estimate of the time-varying circulation over the 11-year time interval 1992 through 2002. Results are described in detail by Köhl et al. (2005). The estimates are consistent with the model equations and have none of the artificial sources or sinks of momentum, heat and freshwater that are common to most assimilation efforts. To bring the model into agreement with observations, its initial temperature and salinity conditions are permitted to change, as are the time-dependent surface fluxes of momentum, heat and freshwater. The estimated "control variables" are largely consistent with accepted uncertainties in the hydrographic climatology and meteorological analyses. Estimated time-mean horizontal transports of volume, heat and freshwater, largely underestimated in the previous 2° optimization (*Stammer et al.*, 2003) have converged with time-independent estimates from box inversions over most parts of the world ocean. Trends in the model's heat content are slightly larger than those reported by Levitus and correspond to a global net heat uptake of about 1.1 W/m^2 over the model domain. Associated abyssal temperature and salinity trends are complex in their geographical patterns and are primarily located in water mass formation regions. Adjustments point toward air-sea interaction in the Southern Ocean and the North Atlantic as a primary reason for deep temperature changes, but also toward potentially incorrect northern boundary conditions in the North Atlantic. The associated model drift in sea surface height over the estimation period is consistent with observations from

TOPEX/POSEIDON over most of the global ocean. Sea surface height changes in the model are primarily steric but show a contributions of mass redistributions from the subpolar North Atlantic and the southern Ocean to the subtropical Pacific gyres. Steric contributions are primarily temperature-based but are partly compensated by salt variation. However, the North Atlantic and the southern ocean reveal a clear contribution of salt to large-scale sea level variations.
Fig. 1 shows the mean flow field at 27m and 1975 m depth from the 1° WOCE synthesis calculation, together with the mean sea surface height and the temperature field at 1975 m. All major circulation structures are simulated, but are smooth due to the present low model resolution.

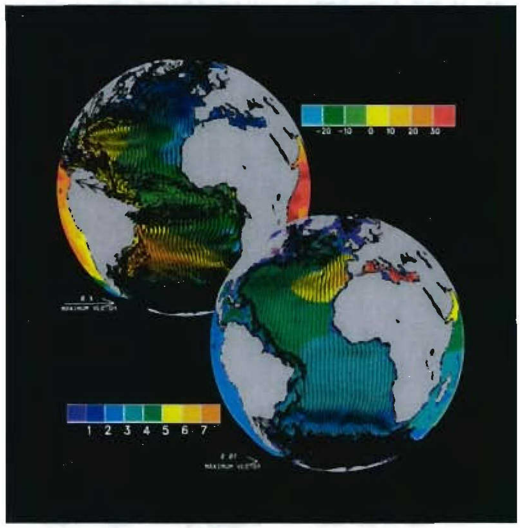

Figure 2: ***Example of the ongoing WOCE synthesis on 1° resolution for the near surface and the deep circulation. The figure shows the estimated mean sea surface height and near-surface velocity field (top) as well as the flow and temperature fields in about 2000 meter depth. See Stammer et al. (2002a,b,c) for details.***

3. Surface Flux Estimates

To bring the model into consistency with the observations, the initial potential temperature (θ) and salinity (S) fields are modified, as well as the surface forcing fields and internal model mixing coefficients. Changes in those fields (often referred to as "control" terms) are determined as a best-fit (in a least-squares sense) of the model state to the observations and their uncertainties over the full data period. We note that this approach therefore allows to estimate surface fluxes of momentum, heat and freshwater and their uncertainties that are required to bring ocean models into consistency with ocean.

The mean net surface heat flux field as it results from the optimization is displayed in the upper panel of Fig.3. Its time-mean change relative to the prior NCEP field is provided in the lower panel of the figure. Changes are on the order of $\pm$ 20 W/m^2 and are over all consistent with prior information about the NCEP flux uncertainties. Similar changes are also obtained for wind stress and net surface freshwater

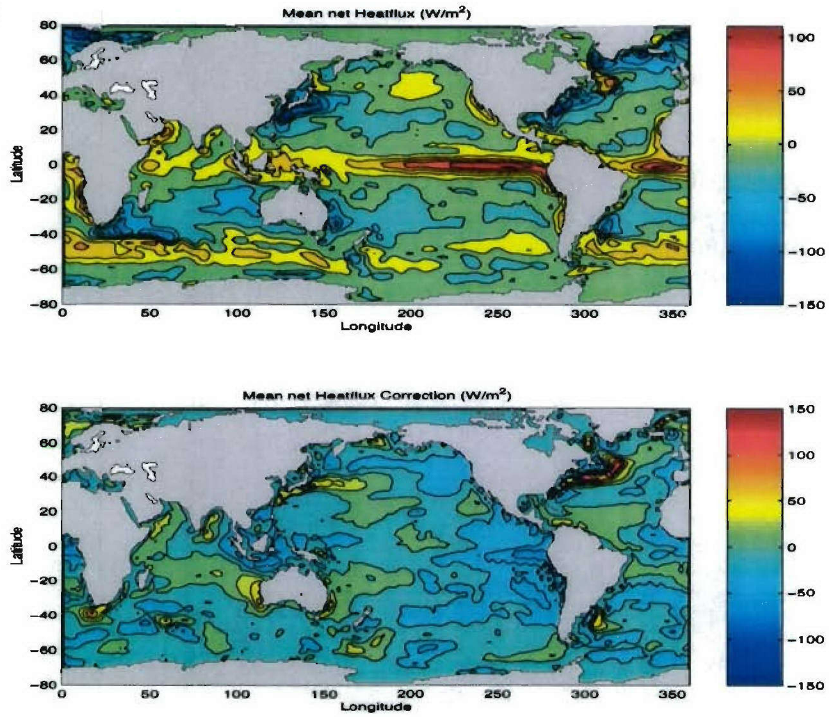

Figure 3: ***The mean net surface heat field as it results from the optimization is displayed in the upper panel. Its mean change relative to the prior NCEP fields is provided in the middle panel. All resulting modifications of the net NCEP heat fluxes, which are of the order of ± 20 W m^{-2} over large parts of the interior oceans and reach ± 80 W m^{-2} along the boundary currents, are consistent with our prior understanding of NCEP heat flux errors.***

Fig. 4 shows zonally integrated meridional heat fluxes for the global ocean. The green open circles show the zonal integrals as obtained by *Ganachaud and Wunsch* (2000). Although our estimates agree with theirs surprisingly well in the Southern Hemisphere and in the North Pacific, large discrepancies exist over the Atlantic where we estimate only about 50% of their amplitude, except at 10°N and at the southern end of the picture. However, this result is unsurprising in a 2° lateral resolution model in which the boundary currents are sluggish and diffuse, with the data unable to impose a different, sharper, spatial structure. Despite this resolution problem, the gross pattern of North Atlantic poleward heat flux is reproduced and its dependence on the closed nature of the poleward model boundaries or other model parameters has to be investigated. See *Stammer et al.* (2004) for a detailed discussion of resulting surface fluxes.

4. Including Model Errors into the Control Vector

Stammer (2005) describes an experiment in which mixing coefficients were included as control parameters: He presented an attempt to estimate geographically varying fields of horizontal and vertical viscosity and diffusivity within a 9-year long estimation procedure. The estimated coefficients are highly efficient in preserving water mass characteristics and frontal structures by

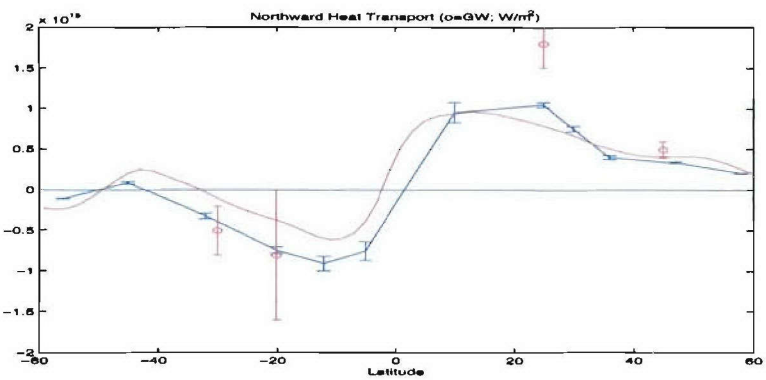

Figure 4: ***Integrated time-mean meridional heat transports for the global ocean estimated for various zonal sections in the model (blue curve). The blue error bars are estimated as $\sigma/\sqrt{N}$. The green error bars mark the standard deviation obtained from individual annual mean estimates. The red curve represents the ocean heat transport inferred from estimated surface heat fluxes.***

reducing the models temperature and salinity drift, especially around the southern ocean. The estimated mean circulation results in stronger transports of western boundary currents and of the Antarctic Circumpolar Current. Moreover, an increase of about 10% in the strength of the Meridional Overturning Circulation (MOC) and in the poleward heat transport can be found. Estimated changes in the horizontal mixing coefficients seem to agree with the notion that diapycnal mixing is superficially high with Laplacian mixing formulations, especially close to frontal structures in the ocean. In comparison with adjustments in tracer diffusivities (vertically and horizontally), adjustments of viscosity coefficients are fairly minor outside lateral boundary regions, suggesting that state estimation attempts might be most successful in providing enhanced insight into tracer mixing.

5. MOC Sensitivity Study and Observing System Design

Köhl (2005) computed sensitivities of MOC and used optimal observations to investigate the overturning stream function in the North Atlantic at 30 degrees N and 900-m depth. Those observations are designed to impact the meridional overturning circulation (MOC) in numerical models maximally when assimilated and therefore establish the most efficient observation network for studying changes in the MOC. They are also ideally suited for studying the related physical mechanisms in a general circulation model. Optimal observations are evaluated here in the framework of a global 1 degrees model over a 10-yr period. Hydrographic observations useful to monitor the MOC are primarily located along the western boundary north of 30 degrees N and along the eastern boundary south of 30 degrees N. Additional locations are in the Labrador, Irminger, and Iberian Seas. On time scales of less than a year, variations in MOC are mainly wind driven and are made up through changes in Ekman transport and coastal up- and downwelling. Only a small fraction is buoyancy driven and constitutes a slow response, acting on time scales of a few years, to primarily wintertime anomalies in the Labrador and Irminger Seas. Those anomalies are communicated southward along the west coast by internal Kelvin waves at the depth level of

Labrador Sea Water. They primarily set the conditions at the northern edge of the MOC anomaly. The southern edge is mainly altered through Rossby waves of the advective type, which originate from temperature and salinity anomalies in the Canary Basin. Those anomalies are amplified on their way westward in the baroclinic unstable region of the subtropical gyre. The exact meridional location of the maximum MOC response is therefore set by the ratio of the strength of these two signals.

2. Testing new Geoid Fields

In parallel new GRACE geoid models were used to test the sensitivity of the estimate to details of the geoid (Stammer et al., 2005). New geoid height estimates, available from the Gravity Recovery and Climate Experiment (GRACE) spacecraft, are critically assessed with respect to their impact on oceanic state estimation, and the implications of a hypothetical, far more accurate geoid are explored. Circulation estimates were obtained over the period 1992-2002 by combining most of the available ocean data sets with a global general circulation model on a 1^{o} horizontal grid. The GRACE-based (GGM01s) estimate of the ocean circulation is then compared to that from a previous estimate using the EGM96 geoid model. When combined with altimetric data, the use of the GRACE geoid leads to fields that are more consistent with a temperature and salinity climatology, and the optimization thereby requires smaller adjustments to the initial model conditions, as compared to the EGM96-based solution. The result supports, but does not prove, the inference of greater geoid skill. Oceanographic implications of the changes are comparatively modest—consistent with earlier studies focused on the time-mean flow alone. To both understand the extent to which the modest shifts are a consequence of a non-fully converged optimization and to understand the impact of a very much more accurate geoid, an additional experiment was performed in which the geoid error was artificially greatly reduced. Adjustments occur then in all aspects of the ocean circulation, including changes in the meridional overturning circulation and the corresponding meridional heat transport in the Atlantic, of about 10% of their mean values. The result shows that the oceanographic implications are quantitatively important, but regional shifts will be very difficult to test by independent means. The error budget of existing time dynamic topography estimates may now be dominated by residual errors in altimetric corrections and these need to be better understood before even present geoid estimates can be fully used in ocean studies.

6. Studying the Pacific Circulation

Interannual variability of the circulation in the Northeast Pacic Ocean is explored by Doughlas et al. (2005) through a joint analysis of expendable bathythermograph (XBT) and expendable conductivity- temperature-depth (XCTD) data, satellite altimetry, and output from a model that was constrained by ocean data. XBT temperature proles with high spatial resolution are available in the eastern North Pacic along two repeated transects. These ship tracks, along with the coast of North America, dene a closed box which is used to study the time-mean circulation and its variability on interannual time scales. Geostrophic velocities from XBT data are compared with geostrophic velocities from model output as well as the full model velocity elds. Correlations in variability on interannual time scales between transport in the subpolar gyre and in the subtropical gyre are present in both model output and data. The nature of the variability, and its relation to the changes of the strength of the North Pacic Current (NPC), which supplies the water for both gyres, are explored. Interannual variability in gyre transport is found to be related to both the bifurcation of the NPC, resulting in an anticorrelation in transport between the two gyres, and to variations in NPC strength, resulting in simultaneous changes in the two gyres. The dominant signal is found to be a long-term increase in the NPC, which results in a strengthening of the subtropical gyre. Possible connections with local-scale wind stress changes and with the El Nino/Southern Oscillation phenomenon are also explored.

7. Improving the Tropical Pacific Circulation Estimates

Hoteit et al (2005a) used the MIT general circulation model (MITGCM) Marshall to study the dynamics of the equatorial Pacific ocean from 1992 to 2000. To achieve eddy permitting resolution at lower cost the model domain is limited to the tropical Pacific, with open boundaries located at $26^\circ N$, $26^\circ S$, and in the Indonesian throughflow. The model domain is nested in an ocean state determined by the consortium for Estimating the Circulation and Climate of the Ocean (ECCO) global assimilation stammer,koehl04 which provides complete ocean products at 1° resolution from an adjoint assimilation system with the MITGCM. Forcing fields, boundary conditions, and model initial conditions are taken from the ECCO global state estimates or from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) re-analysis project. These forcing fields are used in a series of sensitivity experiments. In preparation for later assimilation runs, the model output is compared to ocean observations to evaluate the realism of the flow fields. The comparisons to observations are evaluated for several different 9-year integrations to study the sensitivity of the model to the forcing fields and to the horizontal resolution.

At 1° grid spacing, the regional model produces a solution close to the ECCO global 1° solution, showing that the open boundaries do not strongly change the physics. The increase in resolution to $1/3^\circ$ produces significantly more realistic solutions in many respects, but wind forcing optimized for the 1° global is apparently too strong in certain regions when applied to the $1/3^\circ$ model. Increasing resolution to $1/6^\circ$ does not greatly change the model results. The ECCO heat and fresh water fluxes generally produce clear improvements in model agreement with observations over most of the domain. Various combinations of wind forcing fields produce better model agreement with observations in certain regions of the model domain with neither ECCO nor NCEP winds showing clear superiority. More work must be carried out to improve the quality of the forcing fields, particularly the wind stress for this region.

A variational data assimilation system has been implemented subsequently by Hoteit et al. (2005b) for the tropical Pacific Ocean for an eddy-permitting regional implementation of the MITgcm marshall. The adjoint assimilation system was developed by the Estimation of the Circulation and the Climate of the Ocean (ECCO) consortium stammer, and has been expanded to deal with open boundaries. This system is used to adjust the model to match observations in the tropical Pacific region using control parameters which include initial conditions, open boundaries and time-dependent surface fluxes. This paper will mainly focus on problems related to strong adjoint sensitivities that may impede the model fit to the observations. A decomposition of the velocities at the open boundaries into barotropic and baroclinic modes is introduced to deal with very strong linear sensitivities of the model sea surface height to the barotropic component. Larger viscosity and diffusivity terms are used in the adjoint model to reduce exponentially growing sensitivities in the backward run associated with nonlinearity of the high-resolution model. Simplified experiments in which the model was constrained with Levitus temperature and salinity data, Reynolds sea surface temperature data and TOPEX/POSEIDON altimeter data were performed to demonstrate the controllability of this assimilation system and to study its sensitivity to the starting guesses for forcing and initial conditions.

8. Ocean Angular Momentum Estimates

Ponte RM et al (2002) calculated the ocean angular momentum (OAM) using forward model runs without any data, constraints have recently revealed the effects of OAM variability on the Earth's rotation. Here we use an ocean model and its adjoint to estimate OAM values bg constraining the model to available oceanic data. The optimization procedure yields substantial changes in OAM, related to adjustments in both motion and mass fields. as well as in the wind stress torques acting on the ocean. Constrained and unconstrained OAM values are discussed in the contest of closing the planet's angular momentum budget. The estimation procedure yields noticeable improvements in the agreement with the observed Earth rotation parameters, particularly at the seasonal timescale. The comparison with Earth rotation measurements provides an independent consistency check on the estimated ocean state and underlines the importance of ocean state estimation for quantitative studies of the variable large-scale oceanic mass and circulation fields, including studies of OAM.

9. 50-year Optimization

Still ongoing is a 50-year optimization on a 1 degree spatial grid covering the period 1952 through 2002 using the MIT adjoint model. A first ECCO report is in preparation which describes the data sets that are being used as constraints in the global synthesis obtained by the ECCO Consortium over the 50 year period 1952 through 2002 on a 1° global grid. The report describes the sources of those data sets available before 1992, the applied quality control (QC) and the processing procedure applied prior to the data assimilation effort. The repotr is also complemented by a previous report describing the data available during the period 1992 through 2002. First preliminary results available from the optimization are also summarized.

IMPACTS

The ECCO results, consisting of model fields and related surface forcing are available to the wide community via internet. The ECCO results, consisting of model fields and related surface forcing are available to the wide community via internet through the projects Life-Access-Server (LAS) at http://www.ecco-group.org/las.

The existing legacy is that the entire assimilation system develloped at SIO migrated over to MIT where it is being used now for a sustained some-what delayed but best-possible estimate of the ocean circulation through present using all available ocean data. Estimate do exist through 2004 now and are being continuously updated.

Data assimilation's regular and complete description of the ocean facilitates a wide range of studies in ocean circulation and its applications. This is because it is difficult to make inferences about the ocean continuum from individual measurements without knowledge of the surroundings. Processes controlling the state of the ocean and its evolution can be diagnosed and monitored to help detect and anticipate climate variability. Descriptions of ocean circulation also help understand and quantify the carbon cycle and other biogeochemical processes of the ocean that are affected by advection and mixing (see "TRANSITIONS" below.) Data assimilation contributes to practical applications of oceanography that require complete descriptions of the time evolving flow field and thermal

structure such as fishing, shipping, search and rescue, industrial and naval operations, and weather forecasting. Model-data syntheses also help identify sources of model inaccuracies, providing an objective basis for ocean model improvement. Additionally, data assimilation helps in the design of optimal observing systems by quantifying impacts of different observing strategies on the accuracy of the syntheses.
Finally, the assimilation system itself (adjoint and Kalman filter and smoother) provides a versatile tool for other applications. The assimilation system can be employed to assimilate other data types and/or applied to other configurations including regional and biogeochemical studies. The MIT general circulation model can also be converted to an atmosphere model, and thus provide a system for atmospheric and/or coupled ocean-atmosphere data assimilations. Application of the model adjoint to sensitivity studies is an emerging area of investigation that provides new insight into the workings of complex systems.
The impact of the ECCO project is potentially huge because it is pioneering a new way of doing oceanography. We are demonstrating that global ocean models can be meaningfully constrained by global observations to yield an estimate of the state that is better then either model or observations alone. We believe that the methods being explored in ECCO will become widely used in oceanography and change the way we observe and model the ocean.

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